A Global Record of Single-layer Ice Cloud Properties and Associated Radiative Heating Rate Profiles from an A-Train Perspective

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Introduction

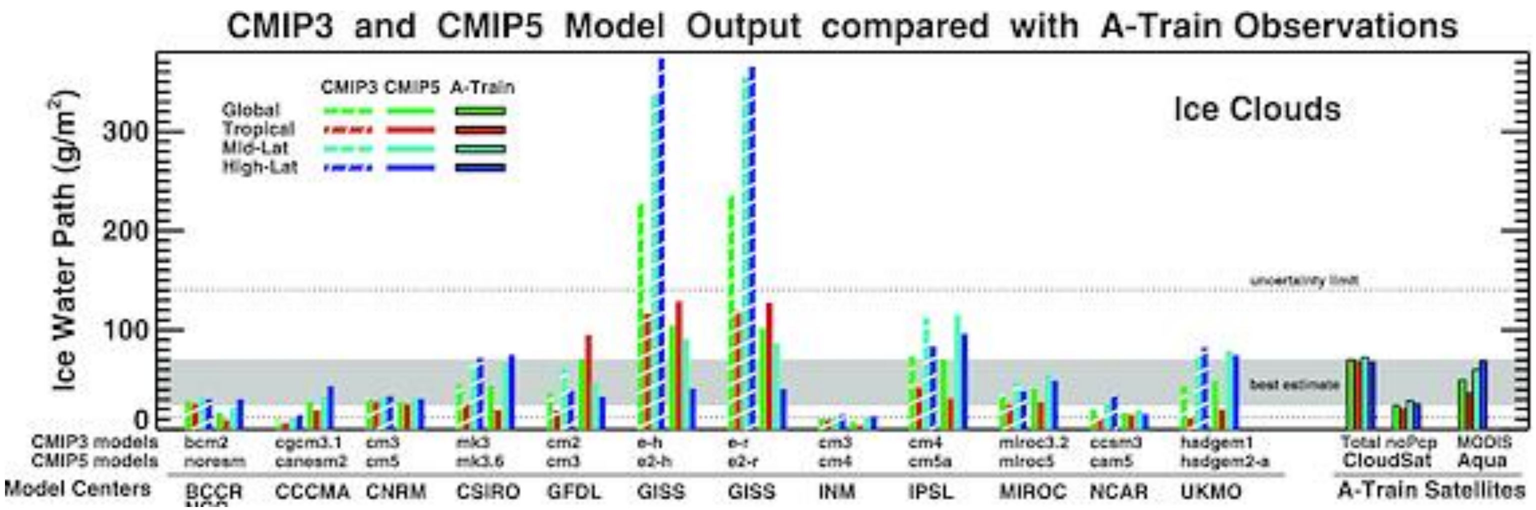
In 2014, we were awarded a NASA Fellowship to study the global radiative heating rate profiles of clouds based on satellite-retrieved cloud properties and in GCMs

- Improve knowledge about the relationship between clouds and radiation in the vertical (thank you, CloudSat and CALIPSO)
- No extensive evaluation of simulated global heating rates in GCMs

Cloud radiative heating rate profiles can be used as a process-oriented diagnostic tool for assessing changes in simulated clouds in global models

Introduction

Improvements in simulated ice clouds in GCMs (CMIP5 vs CMIP3) but biases still exist



Jiang et al. 2012

Vertical structure of ice cloud radiative heating rates is not fully constrained (Cesana et al. 2017)

Selection of single-layer clouds reduces complexity and uncertainty related to cloud overlap assumptions

How do the radiative heating rate profiles of ice clouds vary based on different methods and data?

Methodology and Goals

Step 1

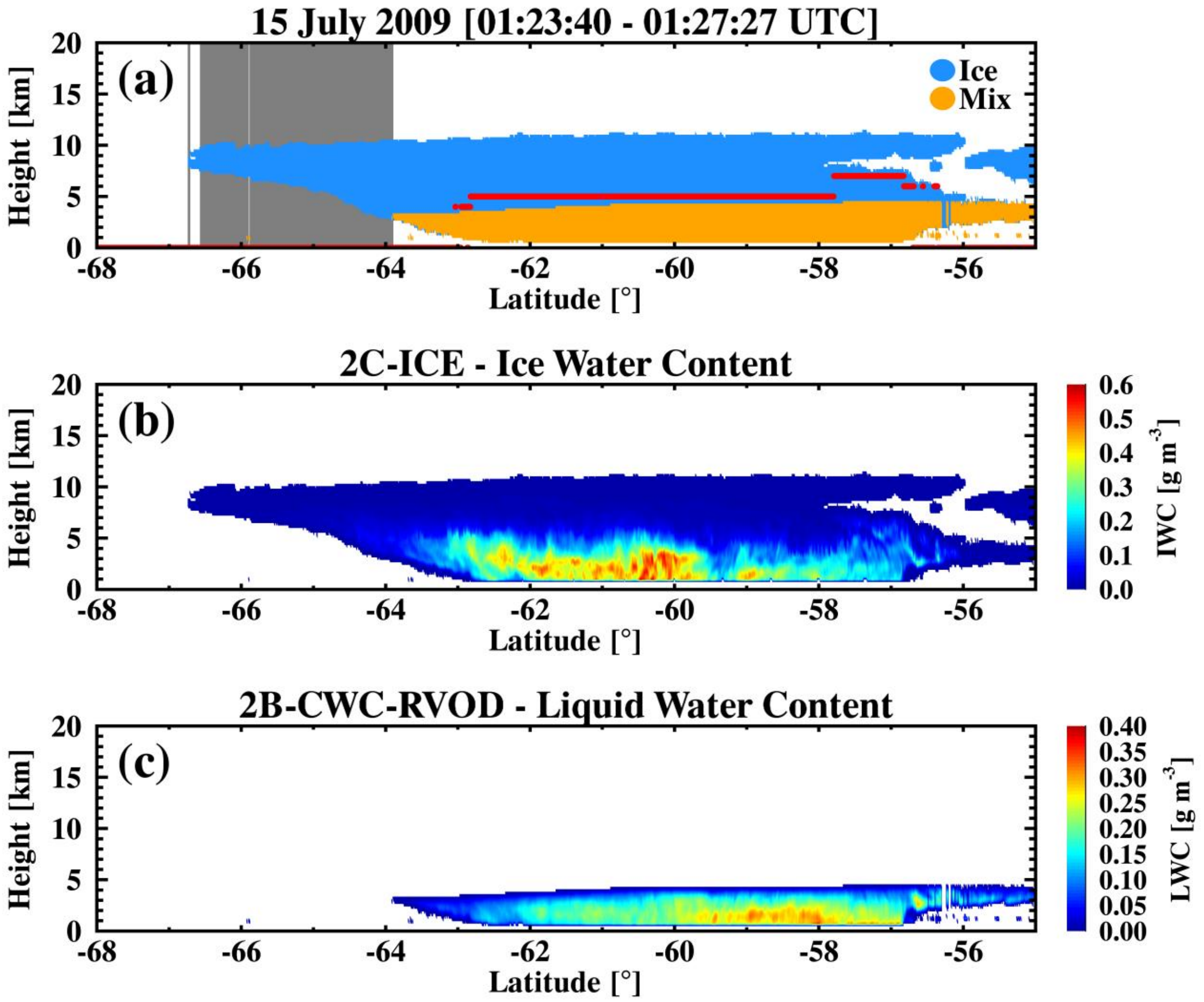
<u>Detection</u>
Sample non-precipitating single-layered ice clouds from CloudSat products

Develop a <u>new</u> record of ice cloud physical and radiative properties

2C-ICE
2B-CWC-RVOD
ECMWF-AUX
2C-PRECIP-COLUMN
http://www.cloudsat.cira.colostate.edu

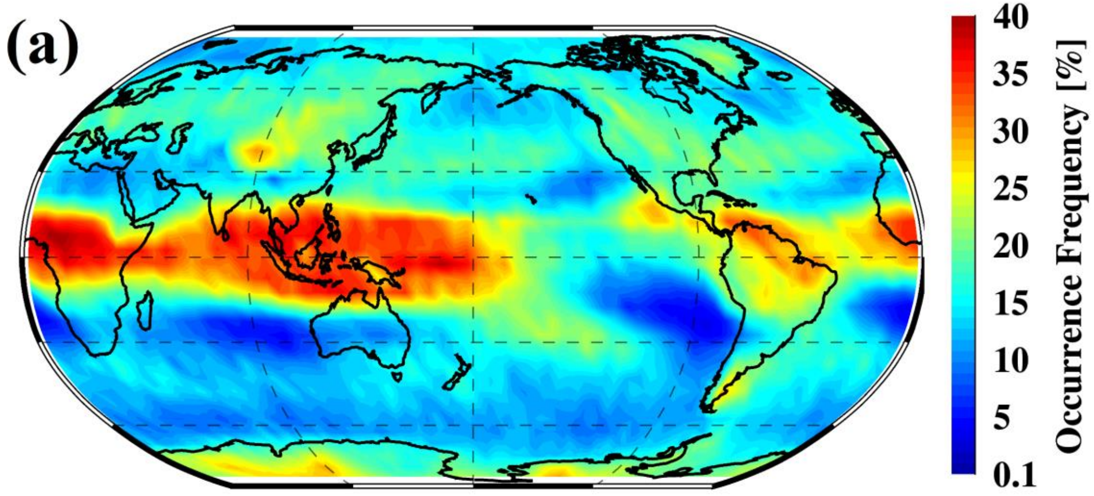
Single-layer Ice Cloud Definition

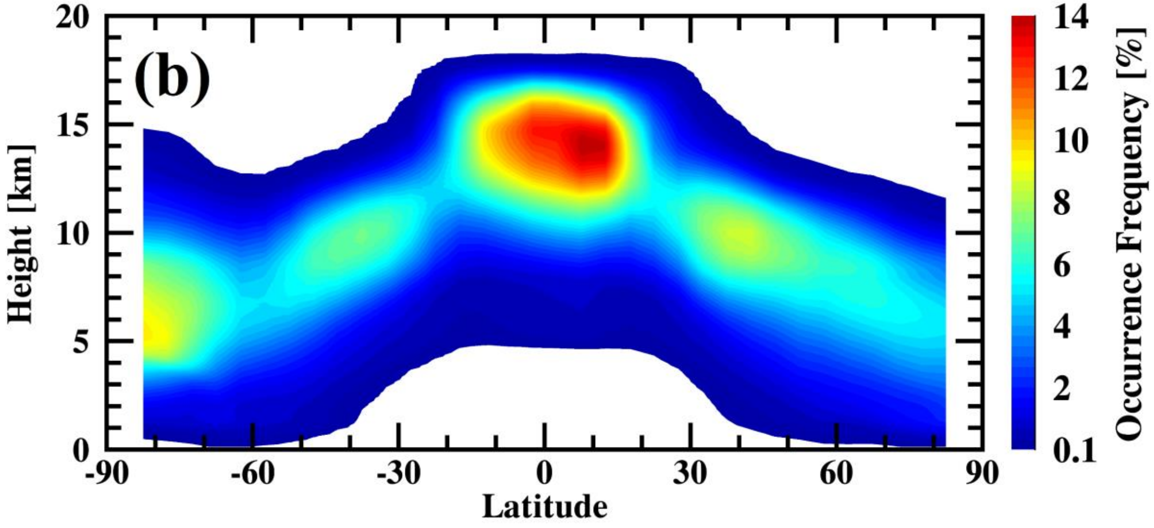
Single-layer, non-precipitating ice clouds are sampled from CloudSat/CALIPSO data



- Retrieved IWC from 2C-ICE is used to identify single-layer ice clouds
- Retrieved LWC from 2B-CWC-RVOD is used to screen for liquid clouds
- Profiles containing detectable precipitation (from 2C-PRECIP-COLUMN) are also removed
- Grey area is region of single-layer ice cloud

Single-layer Ice Cloud Occurrence Frequency





- Global occurrence frequency is ~18%
- Considerably large frequency (> 30%) in the tropics; western Pacific warm pool and in central Africa
- Low occurrence in subsidence areas (i.e., cold, mid-latitude eastern oceans where marine stratocumulus reside)
- Based on the latitude-height distribution, these clouds occur predominately from 12 – 17 km in the tropics and 4 – 8 km in the Antarctic

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Sample non-precipitating single-layered ice clouds from CloudSat products

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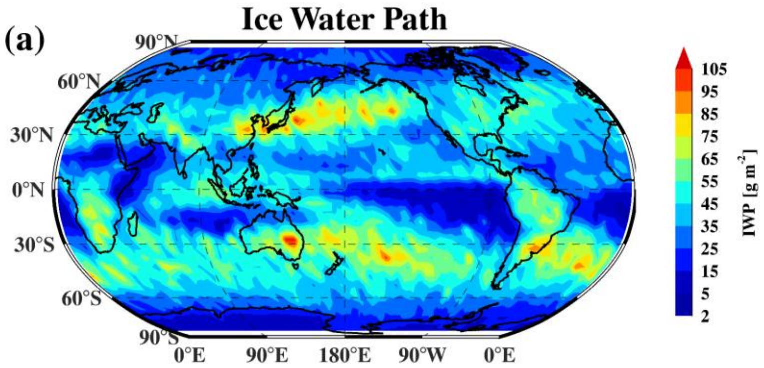
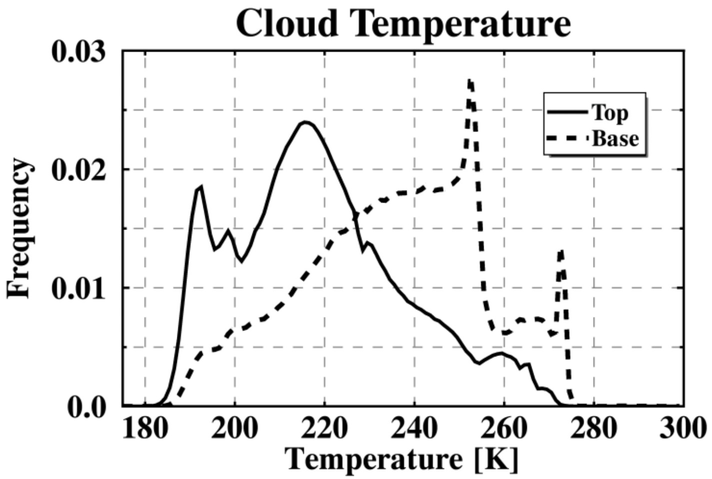
Collocation

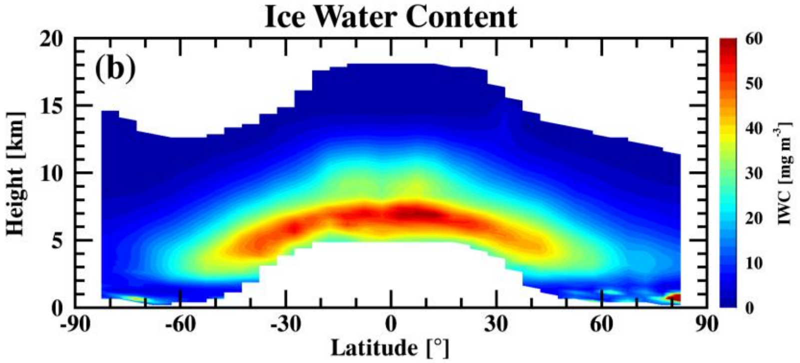
Match sample pixels to CCCM (20 km for CloudSat products)

Non-precipitating Single-layer Ice Cloud Properties



- Global mean ice water path (IWP) is ~40 g m^{-2}
- IWP is largest (50 – 100 g m^{-2}) in tropics and mid-latitudes
- Small IWP in high-latitudes and areas of subsidence

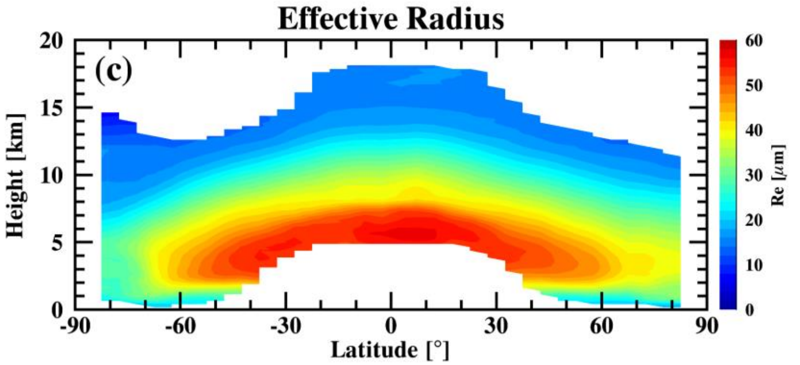


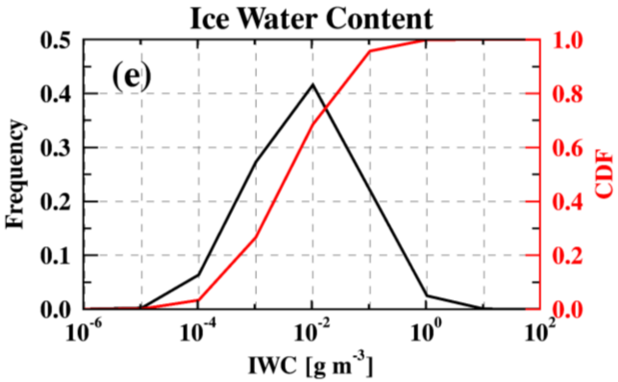


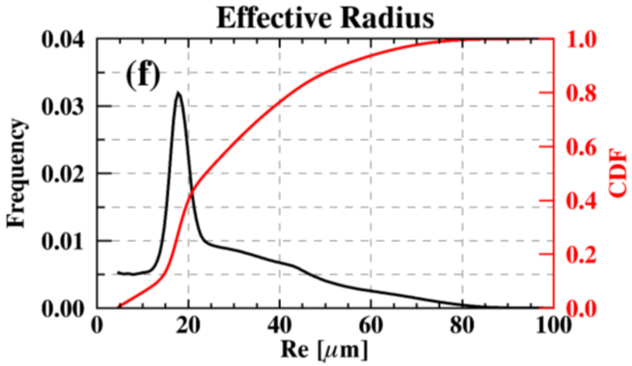
- Ice water content (IWC) and effective radius (R_e) latitude-height cross sections reveal similar patterns
- Largest IWC (50 – 60 mg m^{-3}) and R_e (50 – 60 μm) in the tropics and mid-latitudes at 3 – 8 km

- Several modes of ice crystal types determined by CTT

TTL – 190 K
Cirrus – 215 K
Glaciated ice – 260 K







Methodology and Goals

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Sample non-precipitating single-layered ice clouds from CloudSat products

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Match sample pixels to CCCM (20 km for CloudSat products)

Step 3

Run RTM
with collocated pixel-level data for 4 years of data (2007 – 2010)

Step 4

Compare TOA Fluxes
Of sampled single-layer ice clouds with **2B-FLXHR-LIDAR**, **CCCM_CC**, and CERES

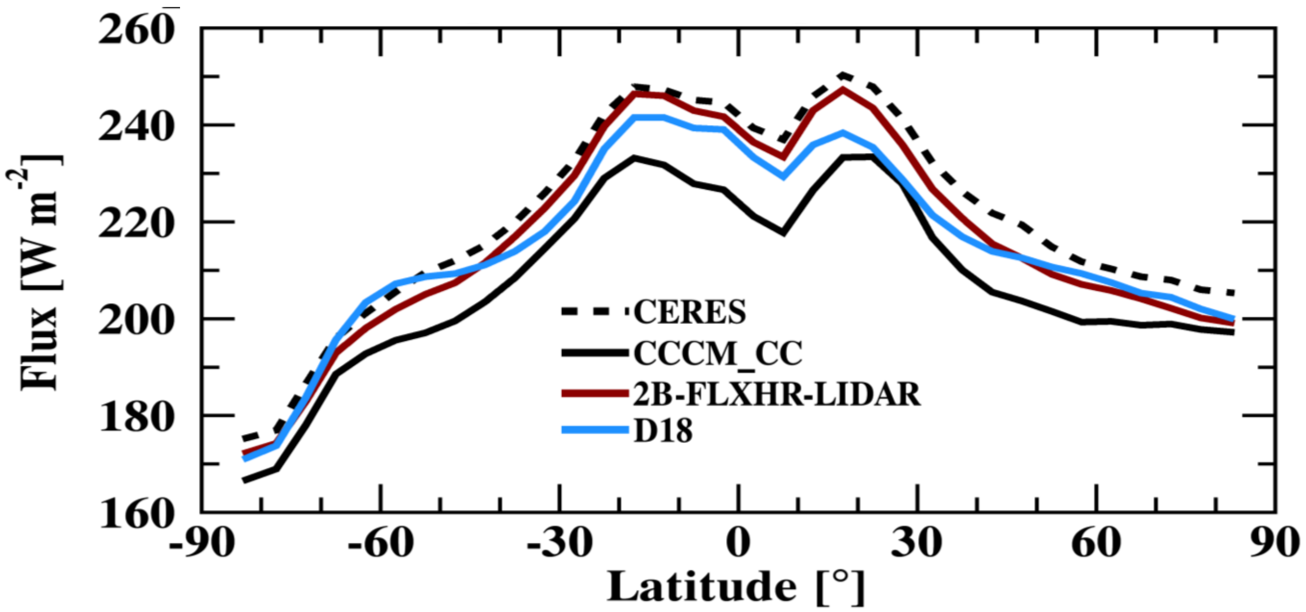
Summary Computed Flux Datasets

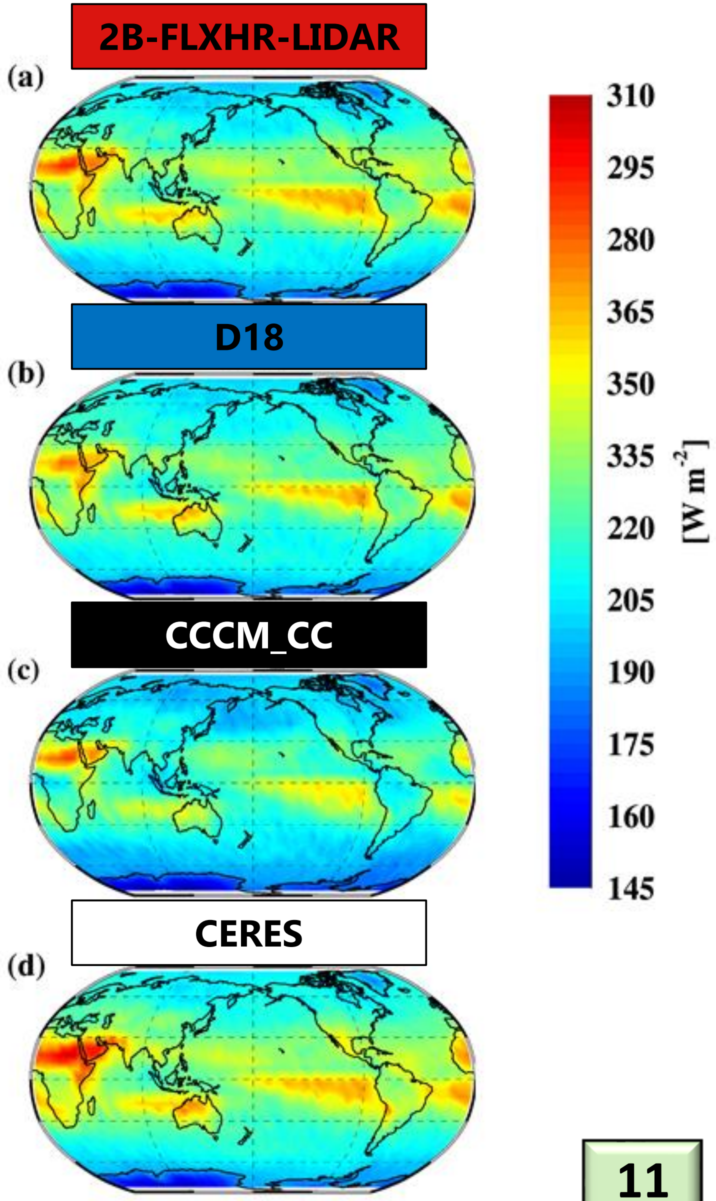
	New! D18	2B-FLXHR-LIDAR	CCCM_CC
RTM	FLCKKR	BugsRad	FLCKKR
IWC/R_e	2C-ICE	2B-CWC-RO, 2B-TAU, CAL_LID_L2_05kmCLay	CloudSat CPR (Revision 4), CALIPSO (V3), MODIS
Meteorology (T, H_2O, O_3)	ECMWF-AUX and MLS	ECMWF-AUX*	GEOS-5
Surface Albedo	CERES/MODIS	IGBP	MODIS
AOD	CALIPSO or MERRA-2**	CALIPSO Level 2 vertical feature mask	CALIPSO, MOD04, MATCH
Aerosol Type	MATCH	CALIPSO Level 2 vertical feature mask	MATCH
Skin Temperature	ECMWF-AUX	ECMWF-AUX	GEOS-4/-5

Caveat: ice model in RTM not consistent with ice model in cloud retrieval, which can lead to differences in flux estimates – increases the global mean SW CRE (–18 vs –32 W m^{-2}) (Yi et al. 2017)

TOA Outgoing Longwave Flux (Daytime)

The TOA outgoing LW flux for not-precipitating single-layer ice clouds from three different calculated flux products and observed from CERES



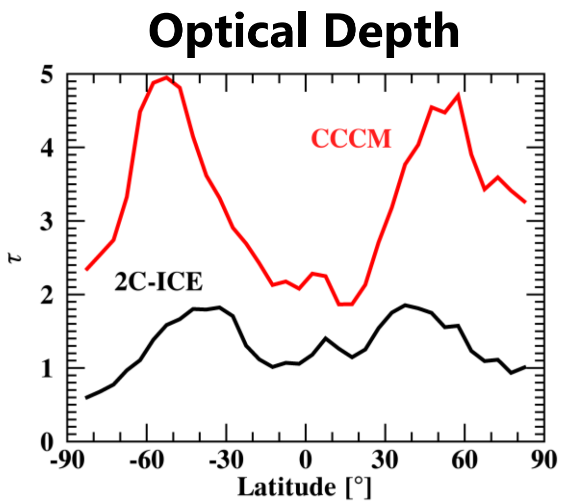


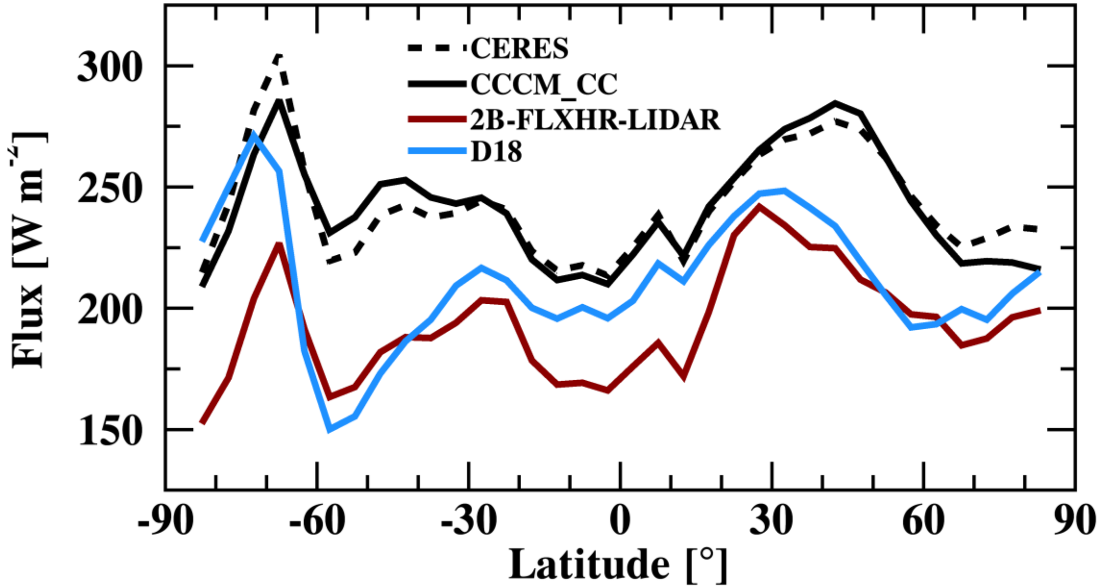
Calculated TOA outgoing LW fluxes match well with CERES

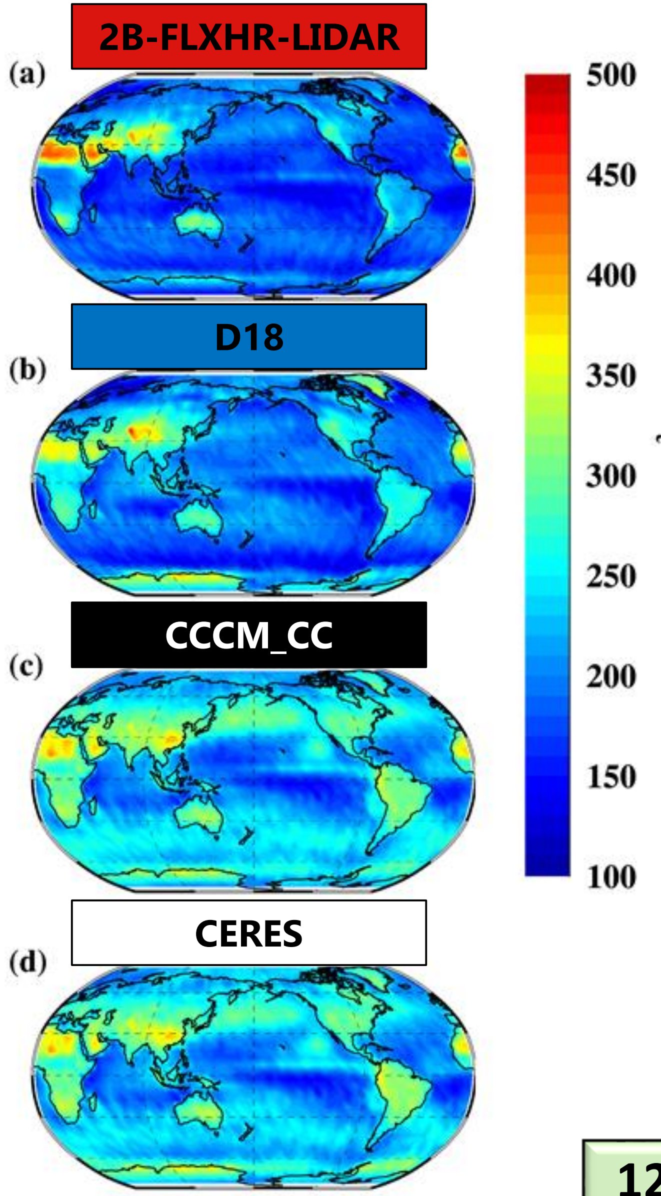
CERES	2B-FLXHR-LIDAR	D18	CCCM_CC
228.7	225.0 (5.6)	222.3 (7.6)	214.6 (14.1)

TOA Reflected Shortwave Flux

The TOA reflected SW flux for not-precipitating single-layer ice clouds from three different calculated flux products and observed from CERES







Calculated TOA reflected SW fluxes are smaller on average compared with CERES/CCCM, which is due, in part, to the difference in cloud optical depth

CERES	2B-FLXHR-LIDAR	D18	CCCM_CC
241.5	194.5 (56.1)	210.2 (44.6)	242.2 (12.2)

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with collocated pixel-level data for 4 years of data (2007 – 2010)

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Compare TOA Fluxes
Of sampled single-layer ice clouds with **2B-FLXHR-LIDAR**, **CCCM_CC**, and CERES

Step 5

Calculate radiative heating rates
Of sampled single-layer ice clouds and compare with **2B-FLXHR-LIDAR** and **CCCM_CC** (tie to commonly simulated GCM parameters)

Radiative Heating Rate Profiles

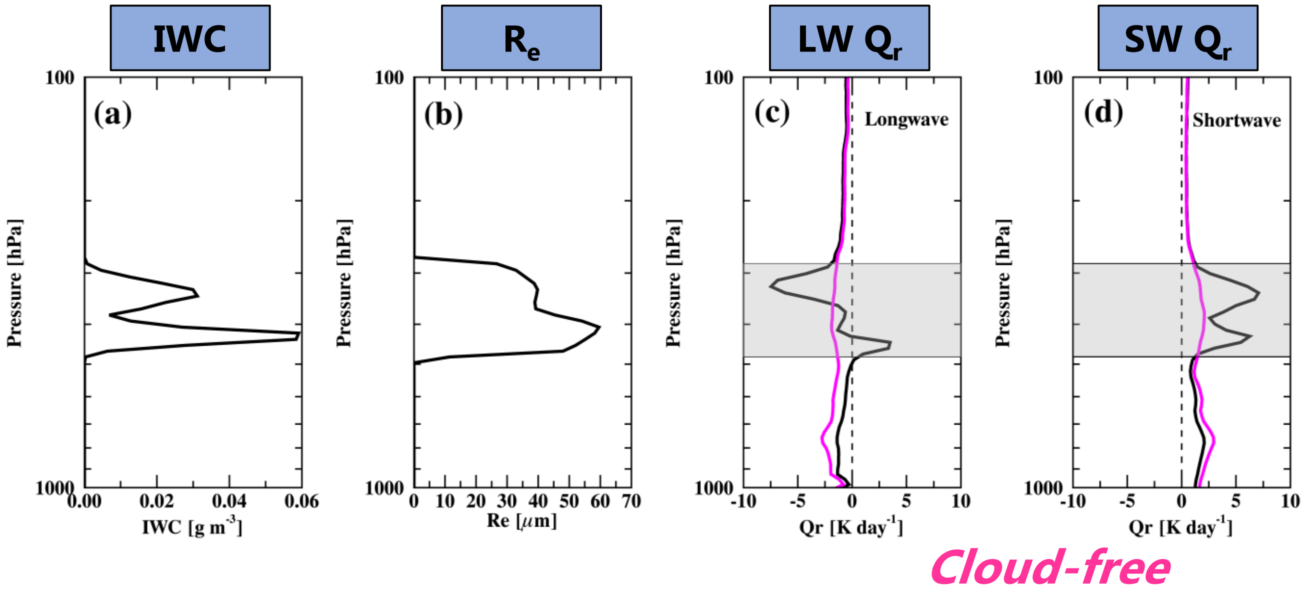
The radiative heating rate profile is determined through calculating the flux divergence within a layer

$$Q_r\ (K\ day^{-1}) = \frac{\partial T}{\partial t} = \frac{g}{c_p}\frac{dF_{net}}{dp}$$

$$\Delta F_{net} = F_{net}(p - \Delta p) - F_{net}(p)$$

$$F_{net}(p) = F^{\uparrow}(p) - F^{\downarrow}(p)$$

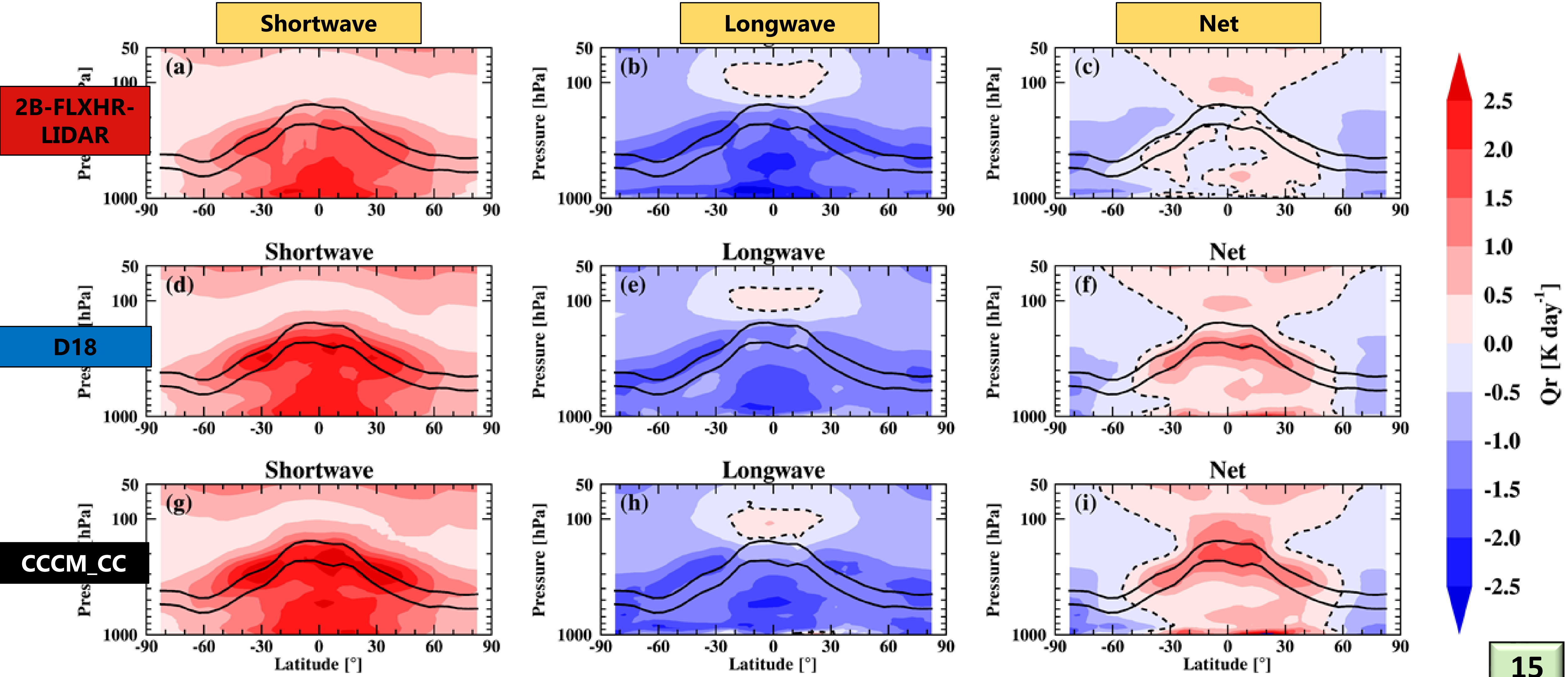
The retrieved IWC and R_e profiles from 2C-ICE (and resulting Qr profiles):



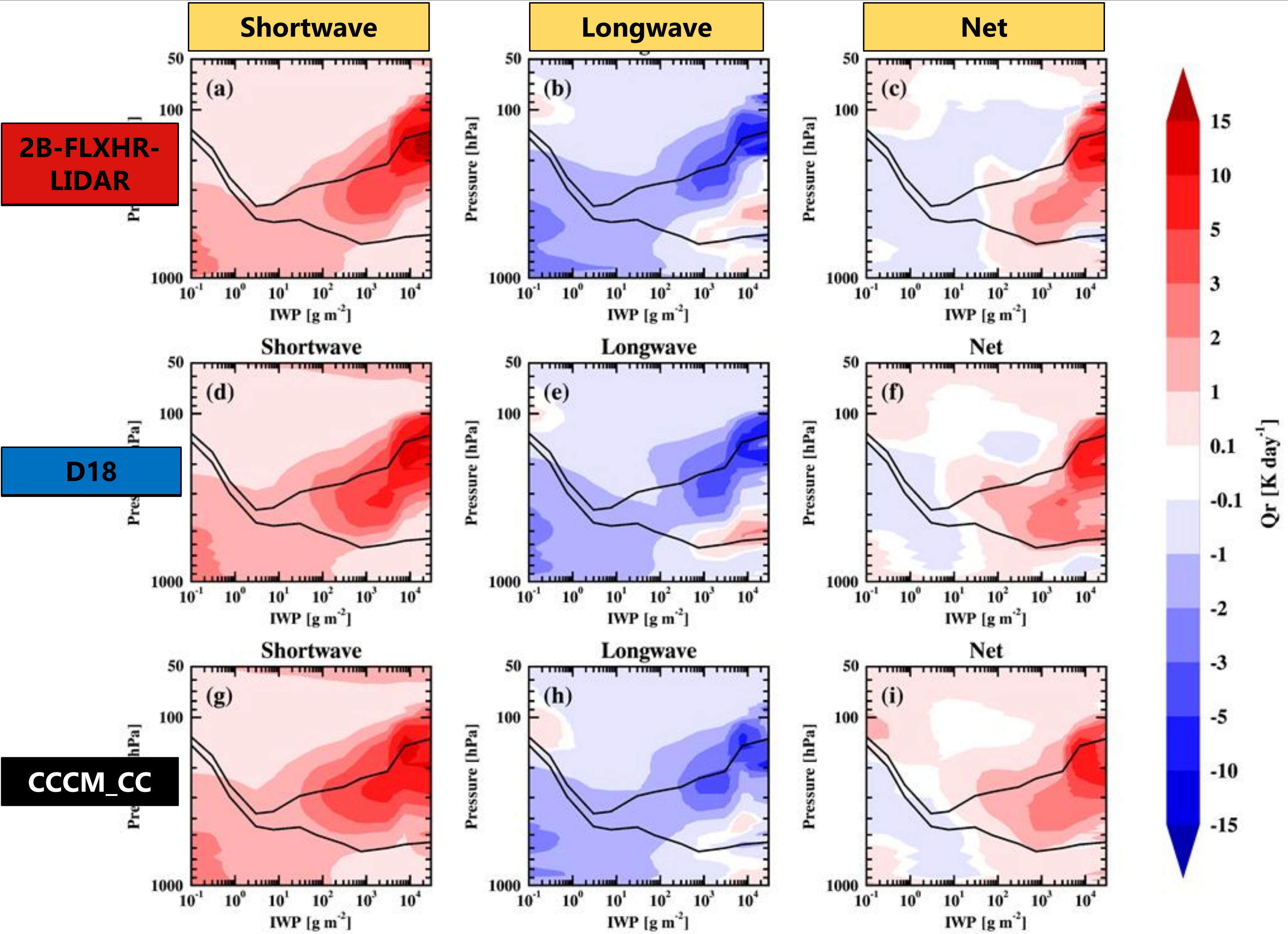
- Cloud vertical structure measured by active remote sensors resolves the vertical structure of in-cloud radiative heating rates
- LW cooling (warming) at cloud-top (-base)
- SW warming through the cloud depth

Zonally Averaged Heating Rate Profiles

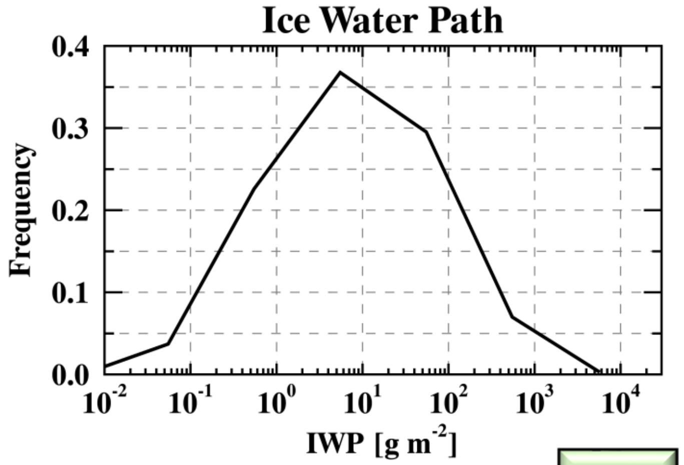
Black lines are the average cloud boundaries from 2C-ICE



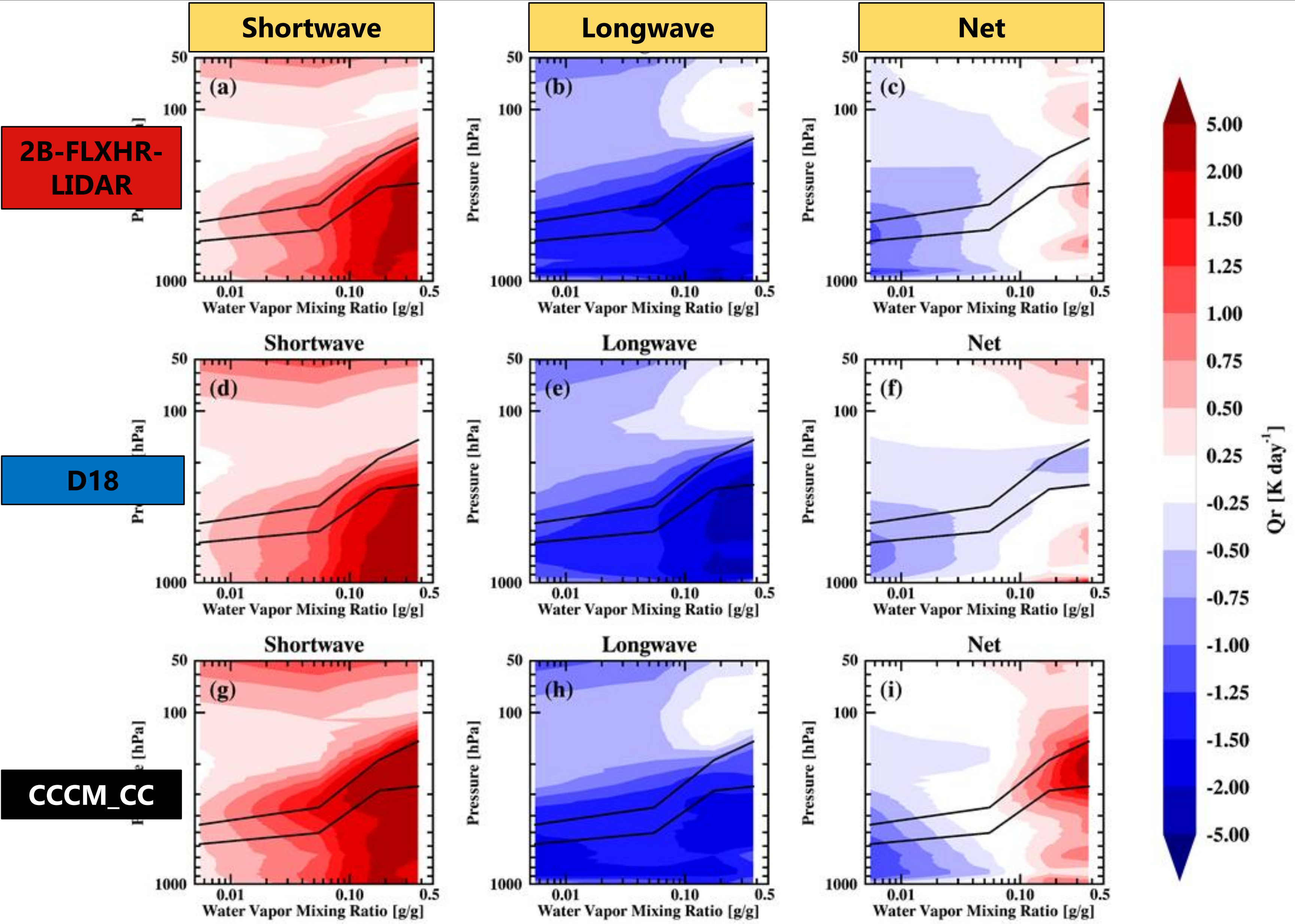
Heating Rate Profiles as a f(IWP)



- Cloud thickness increases with IWP
- Magnitude of SW/net heating and LW cooling increase with IWP
- Strongest Q_r (> 5 K day^{-1}) at large IWP (> 1000 g m^{-2})



Heating Rate Profiles as a *f*(total column water vapor)



- Cloud boundaries ascend from low to high TCWV but the mean thickness does not change much (100 – 150 hPa)
- Higher WV yields stronger Qr within and below the cloud
- LW cirrus cloud signal at TCWV > ~0.1 g/g above ~150 hPa
- Differences in Net Qr profiles at higher TCWV (> 0.1 g/g, ~40% of samples) between the three products suggests clouds in 2B-FLXHR-LIDAR and CCCM_CC are more optically thick than in 2C-ICE

Summary

- Non-precipitating single-layered ice clouds cover approximately 18% of the Earth
    - They occur most often (10-14%) in the tropical warm pool at ~12 – 17 km

- The largest IWP (~ 50 – 100 g m^{-2}), IWC (40 mg m^{-3}), and R_e (50 μm) are in the tropics and mid-latitudes along storm tracks at ~ 4 – 8 km

- Cloud-top temperatures (CTT) suggest several modes of ice types
    - i.e., cirrus (215 K) and glaciated ice (260 K)

Conclusions

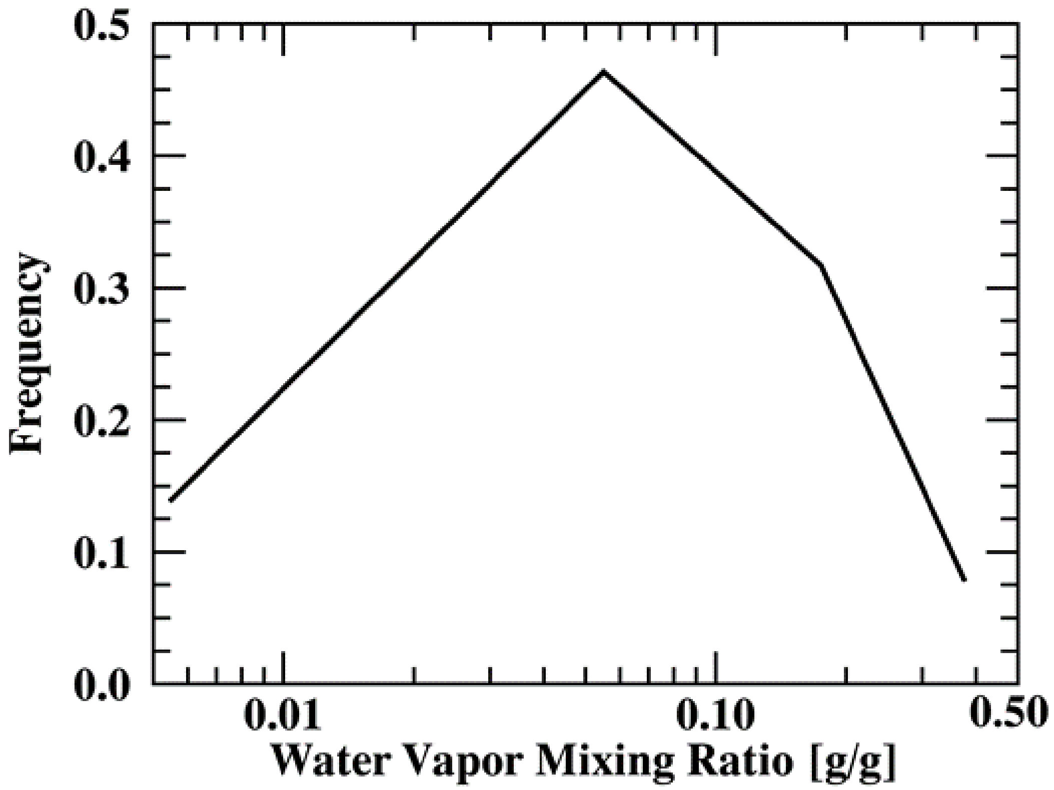
- Net heating rate profiles of single-layered ice clouds suggest that they are most efficient at heating the tropical upper troposphere when the IWP > 20 g m^{-2}

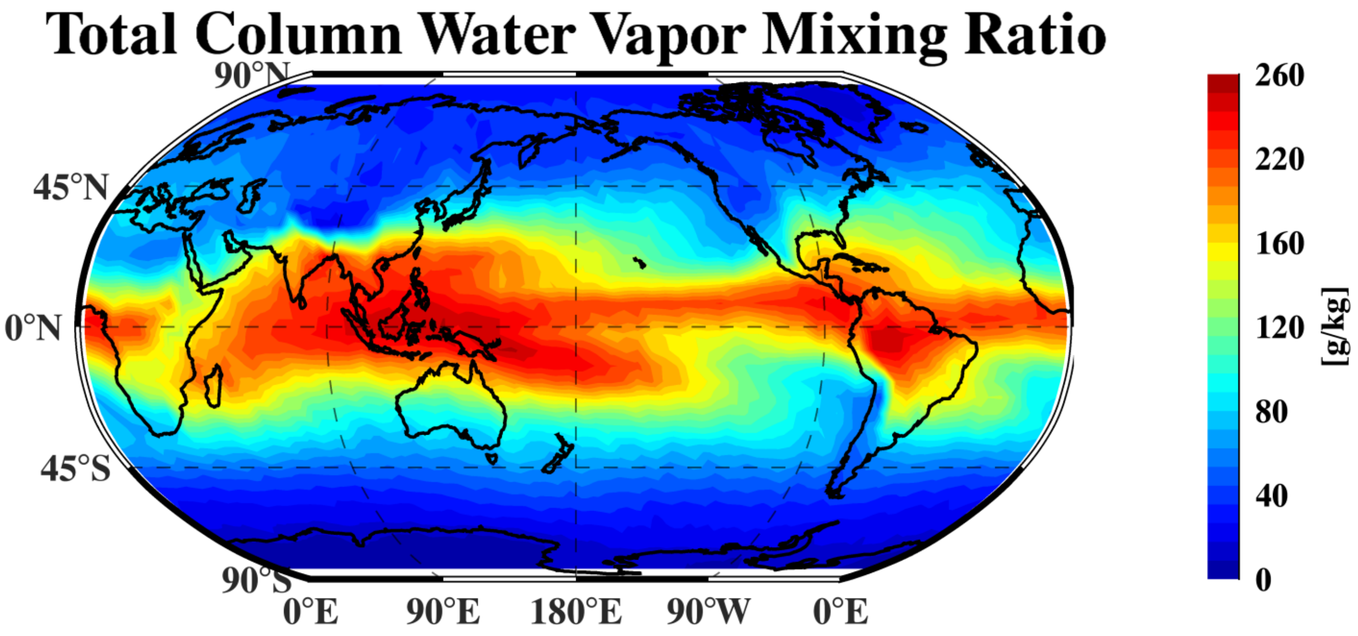
- Differences in heating rate profiles are primarily due to differences in retrieved cloud properties (includes ice cloud retrieval methods themselves) and RTMs (and subsequent ice parameterizations) used

- Range of heating rates supports the idea that ice clouds and their radiative properties are not well constrained

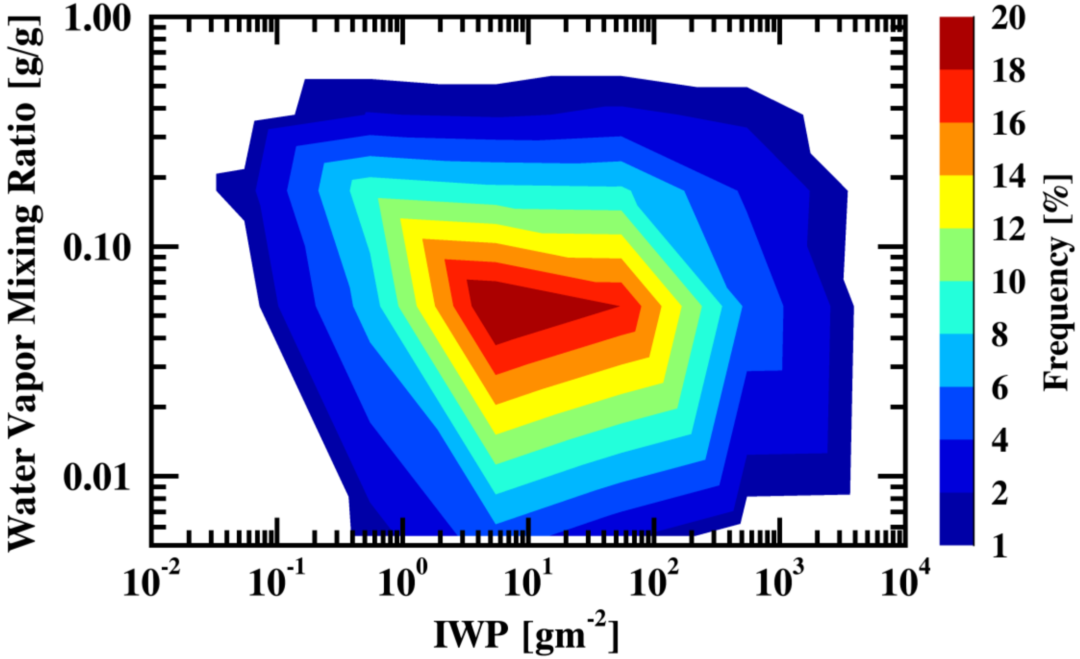
EXTRA

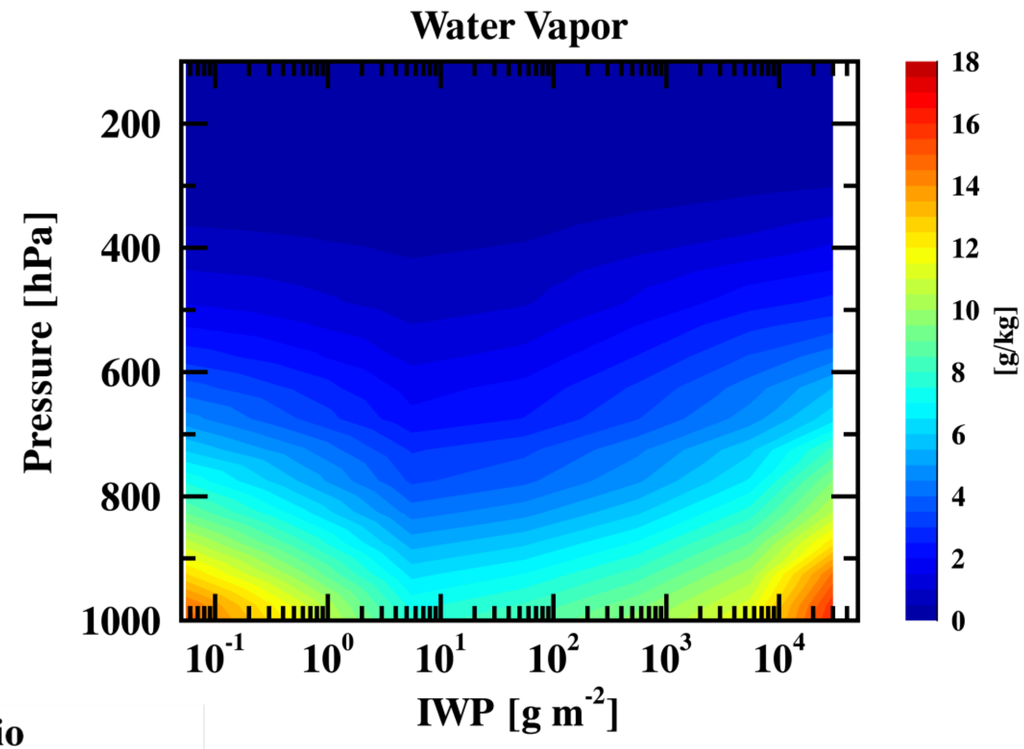
Total Column Water Vapor (TCWV) PDF and Map

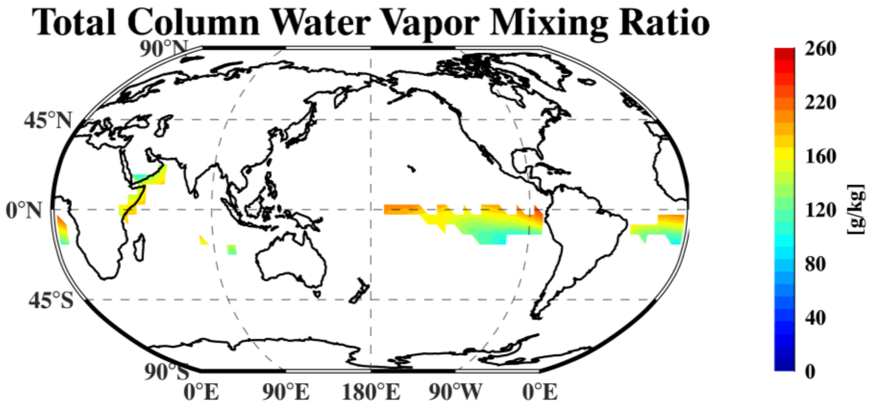




Associating TCWV and IWP

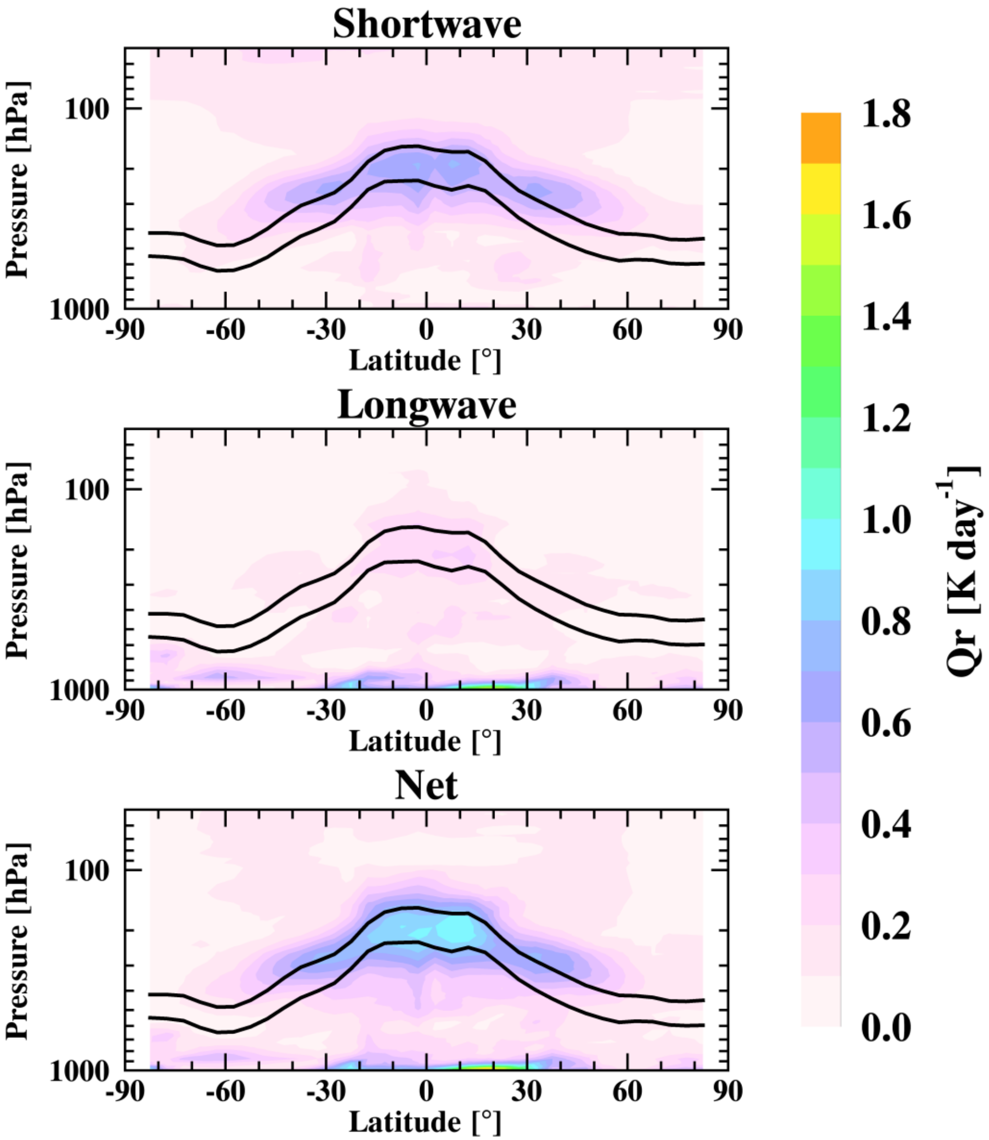






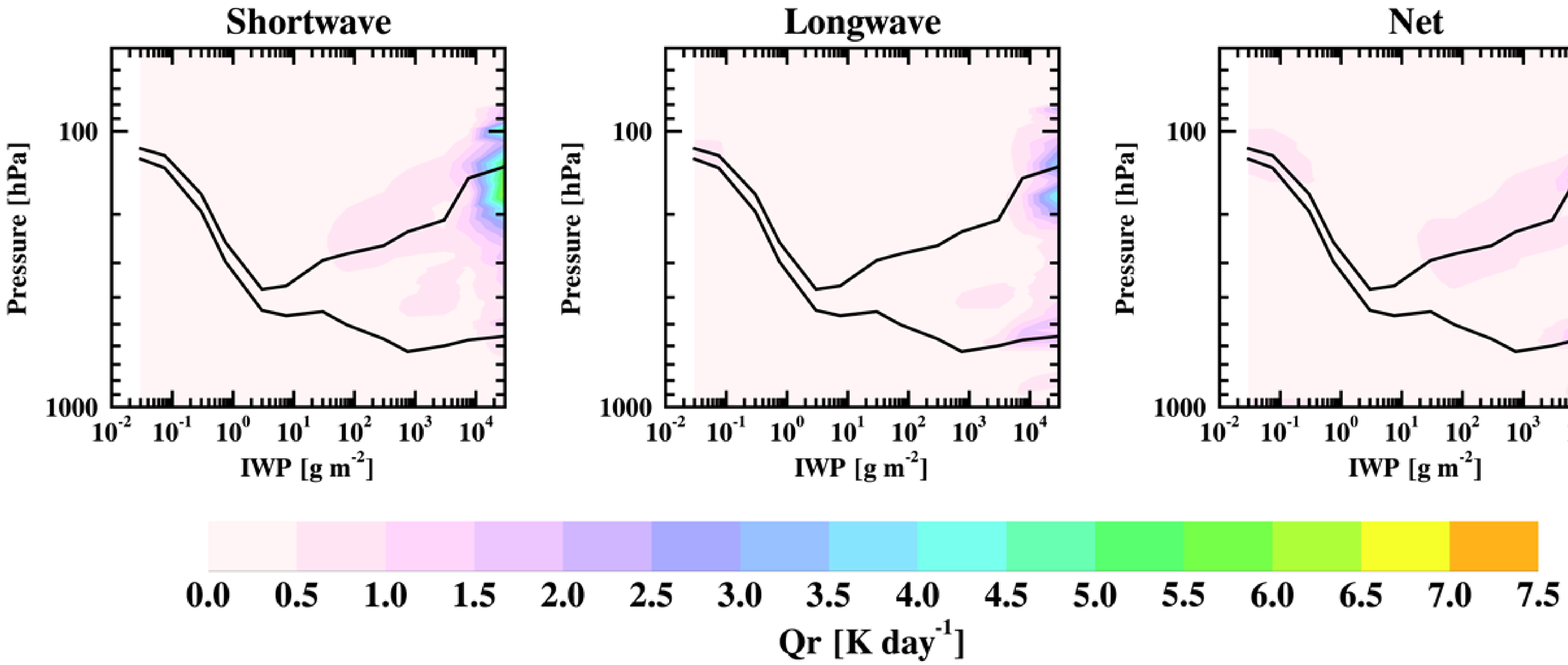
IWP < 20 g m^{-2}
TCWV > 100 g/kg

Standard Deviation of Heating Rates



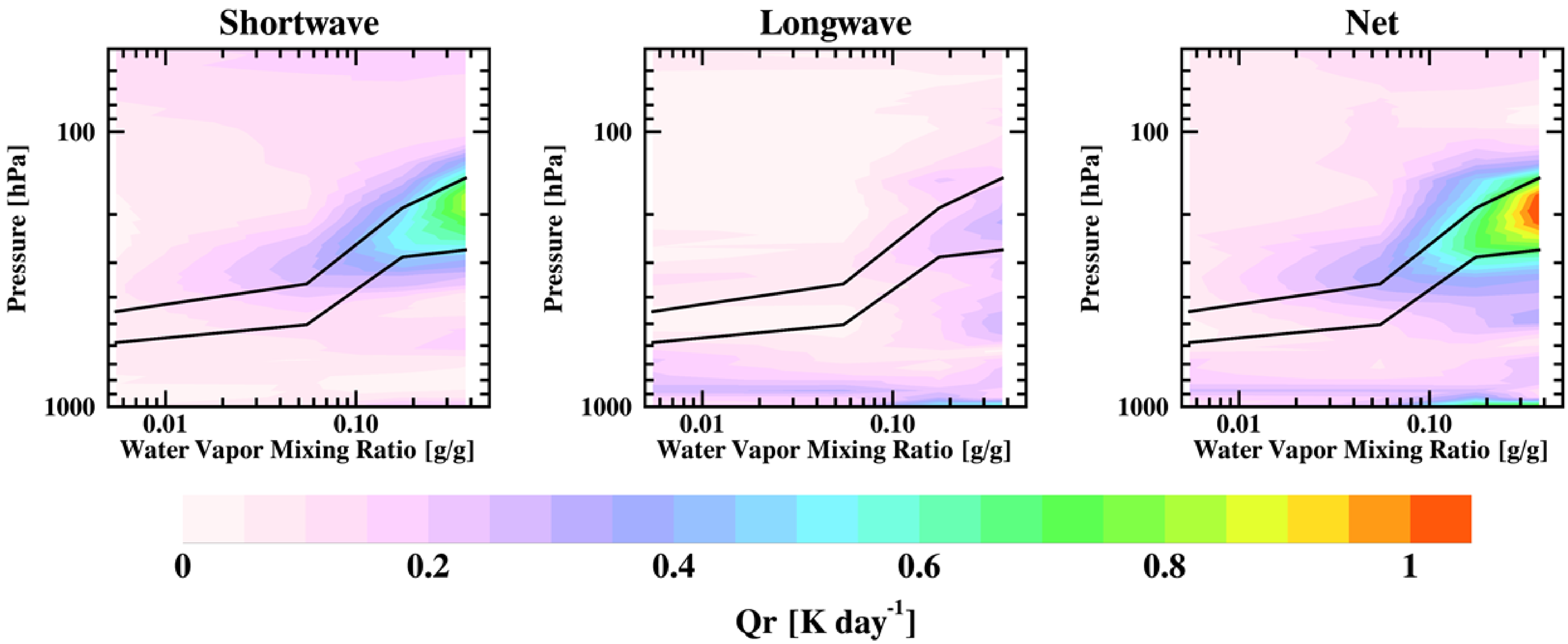
Largest uncertainty, as determined by the standard deviation of the 3 products, is in the tropics within the clouds and near the surface (> 0.6 K day^{-1})

Standard Deviation of Heating Rates



Largest uncertainty, as determined by the standard deviation of the 3 products, is for larger IWP near the cloud-top (> 3 K day–1)

Standard Deviation of Heating Rates



Largest uncertainty, as determined by the standard deviation of the 3 products, is for larger WV (> 0.1 g/g) within the cloud (> 0.5 K day^{-1}) and near the surface